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"Impact Cratering Calculations"

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Final Report

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ACCOMPLISHMENTS:

Overall Technical Approach

This research is computational/theoretical and complements the Caltech experimental program. We have developed an understanding of the basic physical processes and produced computational models and implemented these into Eulerian and Lagrangian finite element codes. The key issues we have addressed include the conditions required for: faulting (strain localization), elastic moduli weakening, dynamic weakening (layering elastic instabilities and fluidization), bulking (creation of porosity at zero pressure) and compaction of pores, frictional melting (creation of pseudotachylytes), partial and selective devolatilization of materials (e.g. CaCO3, water/ice mixtures), and debris flows.

Complex Crater Formation -- Stratigraphy, morphology and impact conditions

One of the key issues associated with the understanding of large scale impacts is how the observable complex crater structural features (e.g., central peaks and pits, flat floors, ring shaped ridges and depressions, stratigraphic modifications, and faults) relate to the impactor's parameters (e.g., radius, velocity, and density) and the non-observable transient crater measures (e.g., depth of penetration and diameter at maximum penetration). We have numerically modeled large-scale impacts on planets for a range of impactor parameters, gravity and planetary material strengths. We used this approach to calculate in detail the initial shock wave driven flow field and carried out these calculations to include the late stage strength and gravity driven motions that finally end in isostatic equilibrium [*O'Keefe and Ahrens*, 1993] . The CTH code [*McGlaun*, 1990], which is an Eulerian shock propagation code that also specifies material constitutive relations. We modified the code to account for the gravitational forces and the interaction with the geologic strength model. The code explicitly calculates the temperature increase due to both the shock heating and plastic work. This heating caused degradation in strength of the material. To describe the dependence of this material strength on dynamic static (gravitational stresses), we used a geologic model [*Jaeger and Cook*, 1979] for both consolidated rock and deep regoliths. This model belongs to the J_2 class of models, where J_2 is the second invariant of the stress deviator. This invariant is a function of pressure, temperature and density [*Cristescu*, 1967]. This strength model allowed us to bound the responses expected from planets with deep regoliths to highly consolidated surfaces and to include the effects of shock and plastic work heating. Moreover, we used the history of deformation strain to specify the degree of microcracking (often called "damage"), and hence, also strength at or close to initial temperatures.

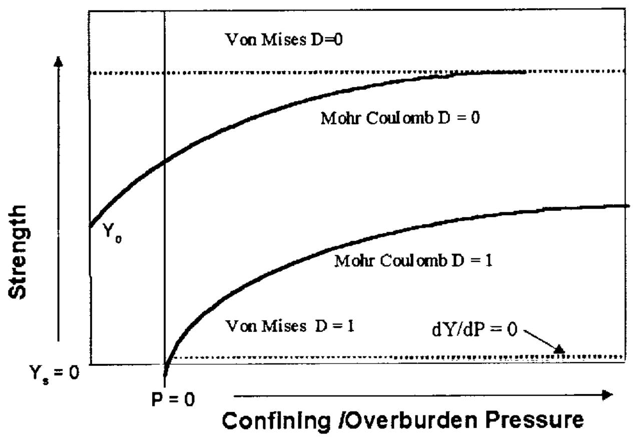

Fig. 1. Geologic strength model including the effects of damage.

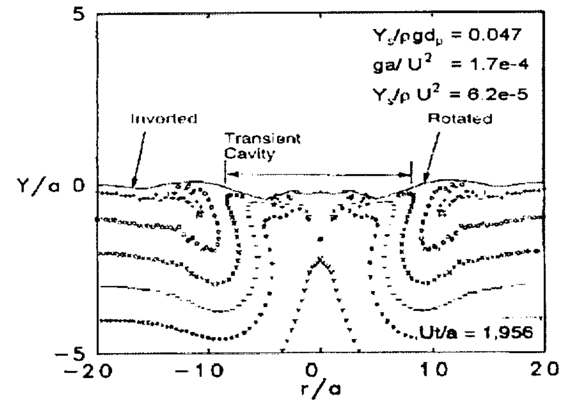

Fig. 2. Complex crater stratigraphy. Relationship between transient cavity diameter and stratigraphy. Note central uplifting.

Upon using the above strength and damage model, we found that the collapse of the transient cavity results in the development of a transient central peak that oscillates and drives surface waves that are arrested by the balance between gravitational forces and planetary strength to produce a wide range of the observed surface features. In addition, we found that the underlying stratigraphy is inverted outside of the transient cavity diameter (overturned flap region), but not inside (Fig. 2). This change in stratigraphy is observable by remote sensing, drilling, seismic imaging and gravity mapping techniques. As given in Figures 2 and 3, the strength which is a function of pressure or depth-Y, and radial position, r, are normalized by the impactor radius, a. The time is normalized by a/U, where U is the impactor velocity. The other dimensionless parameters characterize the impact conditions [*O'Keefe and Ahrens*, 1999], ga/U^2 (inverse Froude no.), $Y_s/\rho U^2$ (inverse Cauchy no.). The number that determines whether or not the calculation is in the simple or complex crater regime is the collapse number, $Y_s/\rho g\ d_p$, where d_p is the depth penetration under zero strength conditions. This is a measure of the strength to overburden pressure ratio.

We used the above results to develop scaling laws (Fig. 3) and to make estimates of the impact parameters for the Chicxulub impact and also compared the calculated stratigraphic profile with the internal structure model developed by Hildebrand et al. [1998], using gravity, seismic and other field data. For a stratigraphy rotation diameter of 90 km, the maximum depth of penetration is ~43 km. The impactor diameter was also calculated. From the scaling relationships for a 2.7 g/cm³ asteroid the impact velocity is 20 km/s. The energetic equivalent of a 1.0 g/cm³ comet must impact at 40 km/s, an impactor diameter of ~13 km is inferred, and for a comet impacting at 60 km/s, an impactor diameter of ~10 km.

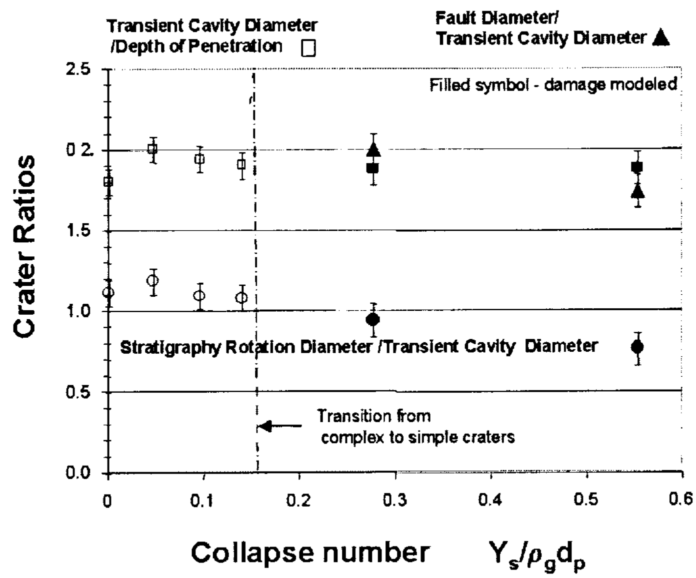

Fig. 3 Key crater parameters without and with the effects of damage. We estimate that damage shifts the transition between simple and complex craters by more than an order of magnitude.

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